V International Conference on Particle-based Methods – Fundamentals and Applications
PARTICLES 2017
P. Wriggers, M. Bischoff, E. Oñate, D.R.J. Owen & T. Zohdi (Eds)

PROCESS SIMULATION OF DEEP PENETRATION LASER WELDING BY COUPLING A SMOOTHED PARTICLE HYDRODYNAMICS MODEL WITH A RAY-TRACING SCHEME

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Key words: Smoothed Particle Hydrodynamics (SPH), Deep Penetration Laser Welding, Heat Transfer, Phase Transition, Ray Tracing, Co-Simulation.

Abstract. Deep penetration laser welding is a preferred joining technique in industry due to high welding speeds and flexibility regarding material and geometry. In deep penetration laser welding, the high intensity of the laser irradiation causes a part of the material to evaporate instantaneously such that a vapor-filled capillary is formed within a few milliseconds. To simulate this laser welding process, the meshless Lagrangian Smoothed Particle Hydrodynamics (SPH) method is applied. For accurate modeling of the laser-material interaction, the SPH simulation is coupled with a ray-tracing scheme. Using this co-simulation technique, the geometry of the capillary is tracked throughout the welding simulation to gain additional insights.

The developed model is able to capture the characteristics of the welding process independently from material and process parameters. An advantage of the simulations compared to experiments is that further values like the absorbed power or intensity distribution at the surface of the material can be continuously obtained. Moreover, the SPH model provides a good estimation for the dimensions of the weld pool. This is demonstrated by means of welding examples with an oscillating laser beam. Therefore, SPH in combination with a ray-tracing scheme is a suitable method for the process simulation of deep penetration laser welding and a valuable tool for finding optimal process parameters, e.g. optimal trajectories for the laser beam to affect the resulting weld to a desired shape.

1 INTRODUCTION

Nowadays laser welding is universally applied for joining tasks in industry. The popularity of laser welding results from its flexibility regarding geometry and material properties, high degree of automation, high welding speeds and narrow heat-affected zones. Weld defects such as pores, spatter, and humping may, however, still occur. Improving the weld quality by reducing weld defects and increasing the process efficiency remain two crucial tasks subject to current research. Experimental data and simulation results complement one another in understanding all physical phenomena occurring during laser welding and in achieving welds with high quality in a more efficient manner.

During deep penetration laser welding, the high intensity of the laser beam leads to instantaneous evaporation of the material at the surface of the workpiece. A vapor-filled capillary is formed that moves with the laser beam through the workpiece. Due to multiple reflections of the laser beam at the capillary walls, the absorption behavior becomes very complex depending on the precise surface geometry.

An overview of different models for deep penetration laser welding is found in [1]. The models use different numerical methods to include main physical aspects during laser welding to a various level of complexity. The main aspects to be modeled are the interaction between laser beam and workpiece, the free-surface melt flow, the heat transfer including all occurring phase transitions, and the fluid-structure interaction between the different phases.

We tackle the modeling process by using a co-simulation approach. The workpiece is modeled based on the meshless Lagrangian Smoothed Particle Hydrodynamics (SPH) [2, 3] method. Being first introduced for astrophysics problems, the applications now range from large deformations in solid structures to free-surface and multi-phase fluid flow problems. The SPH method is applied here for modeling both the solid and liquid phases and the heat transfer including phase transitions. In addition, a ray-tracing scheme is applied that approximates the laser beam through a large number of rays and tracks each ray according to geometrical optics. The co-simulation approach has been presented in [4, 5]. Some numerical examples by applying this method are shown in [6].

In this work, the developed SPH model coupled with a ray tracer in a co-simulation is applied to simulate a laser welding scenario with an oscillating laser beam. In Section 2, the main features of the SPH model for laser welding are outlined. In Section 3, the coupling of the SPH simulation with a ray-tracing scheme and the workflow during the co-simulation is presented. Examples using this co-simulation approach are illustrated in Section 4 for laser welding with beam oscillations. Conclusions and an outlook are given in Section 5.

2 MODELING WITH SPH

In a mathematical sense, the SPH method is a general discretization technique that transforms a system of partial differential equations into decoupled ordinary differential equations. During time integration, the integrals are further simplified into sums of the individual contributions of surrounding discretization points (so-called 'particles') within a specified area given by the smoothing length.

The weakly compressible SPH formulation of Monaghan summarized in [7] is applied for modeling both solid and liquid phases. Heat conduction and heat sources are considered in the model according to [8]. The governing equations for conservation of mass, linear momentum, and energy are extended to a thermomechanically coupled formulation by combining mechanical and thermal deformations and stresses into the same framework [9]. For the liquid phase, temperature-dependent surface tension is taken into account using a model from [10]. Different heat conductivities and heat capacities are specified for the solid and liquid phases to account for the varying material properties. Fluid-structure interaction is modeled at a physical level by unifying the stress tensors for both solid and liquid phases.

The phase changes currently considered in the model are melting, evaporation, and resolidification. The specific enthalpy is used as an equivalent variable of the thermal energy stored in the system. When only small pressure changes are assumed, the increase in enthalpy is approximately equal to the amount of heat added to the system. Therefore, a change in enthalpy may be converted to a change in temperature with the heat capacity as proportionality factor. The latent heat of fusion and evaporation are released or absorbed by the material in a transition range between two phases. During the SPH simulation, when a particle melts or resolidifies, this particle type is dynamically changed from a solid to a fluid particle or vice versa.

The gas phase motion is currently not simulated, and the effects of evaporation are only considered through the recoil pressure acting on the surface of the weld pool. The particles that evaporate are deleted during the simulation after the evaporation has completed. The recoil pressure acting on the surface of an evaporating material due to high-intensity laser radiation is calculated according to [11].

The SPH model is implemented into the software package Pasimodo [12], which is used for the welding simulations.

3 CO-SIMULATION WITH A RAY-TRACING SCHEME

The co-simulation between the SPH simulation in Pasimodo and the ray-tracing scheme as implemented in [13] is based on a server-client architecture, in which Pasimodo acts as the server, and the ray tracer as a client. All required data are exchanged via a TCP/IP network protocol.

The workflow of the co-simulation is briefly described in the following. A more detailed version may be found in [4]. An ellipsoidal plane is used as the initial surface geometry for the ray tracer. The calculated absorbed intensities for each surface triangle are transferred to Pasimodo as initial energy input through the laser beam. In Pasimodo heat source particles are added at the center of gravity positions of each triangle. The transformation of intensities to heat source particles is described in detail in [5].

In Pasimodo the welding simulation is performed with these dynamically added heat source particles. After a user-defined coupling time interval, the current surface geometry is detected and reconstructed. The detection of surface particles follows the method depicted in [14]. Based on the detected surface particles and their approximated normal vectors, the surface of the capillary and weld pool is reconstructed and a triangle mesh is generated.

The updated geometry and the temperature of the surface particles are then sent to the ray tracer in PLY format [15]. Using the updated input data, the ray tracer again delivers the absorbed intensity distribution and sends it to Pasimodo. This co-simulation loop is repeatedly executed until the welding simulation has finished.

4 EXAMPLES

Intentional oscillations of the laser beam are subject to current research in order to influence the resulting weld seam to a desired shape, e.g. a perfect rectangular cross section that is able to withstand higher loads. A further motivation for laser beam oscillations is to stabilize the welding process and to reduce weld defects [16, 17, 18]. Optical systems with increased precision regarding focus position have been developed in the past years such that the laser beam can follow almost arbitrarily given trajectories.

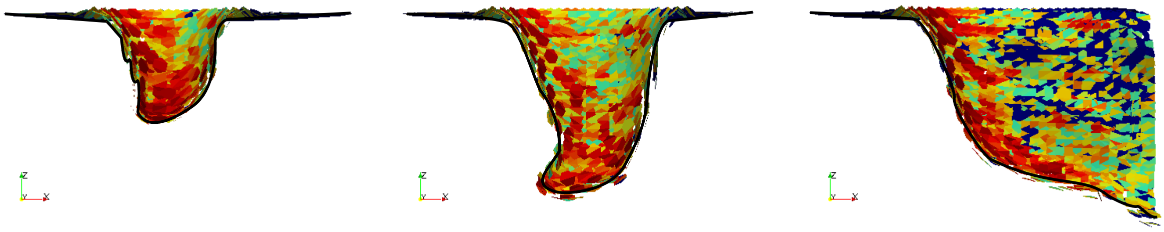
In this section, the first example is the seam welding process of an iron sheet. Afterwards, the laser beam is subjected to an oscillating motion to investigate the impact of these oscillations on the capillary and weld.

4.1 Welding of an iron sheet

In the following example, a seam welding process of an iron sheet is simulated. The discretized workpiece with the dimensions 4 x 2.5 x 2 mm^3 consists of approximately 163000 particles arranged in a rectangular grid at the beginning. A laser with a Gaussian beam profile, a focal diameter of $200\,\mu$m, and a power of 5000 W is applied. The focus position is the upper surface of the workpiece. The feed rate is specified as 6 m/min. The coupling time interval for the co-simulation loop is set to $50\,\mu$s.

During the simulation, a capillary with a depth of 1.11 mm and a width of 0.52 mm is formed through the welding process. Three geometries of the reconstructed capillary with their absorbed intensities are depicted in Fig. 1 which shows the evolution of the capillary over time.

The temperature distribution after 25 ms and the different phases are visualized in Fig. 2. The dark grey particles remained solid during the whole welding process, the blue particles form the liquid weld pool, and the light grey particles shape the resolidified weld seam with a depth of 1.15 mm and a width of 0.87 mm. Since the evaporated particles are deleted during the simulation, these are not shown in the figure.



(a) $t = 2.5\,\mathrm{ms}$ (b) $t = 5\,\mathrm{ms}$ (c) $t = 15\,\mathrm{ms}$

Figure 1: Capillary cross section with intensity distribution (red: high intensity, blue: low intensity) in the xz-plane during welding of iron.

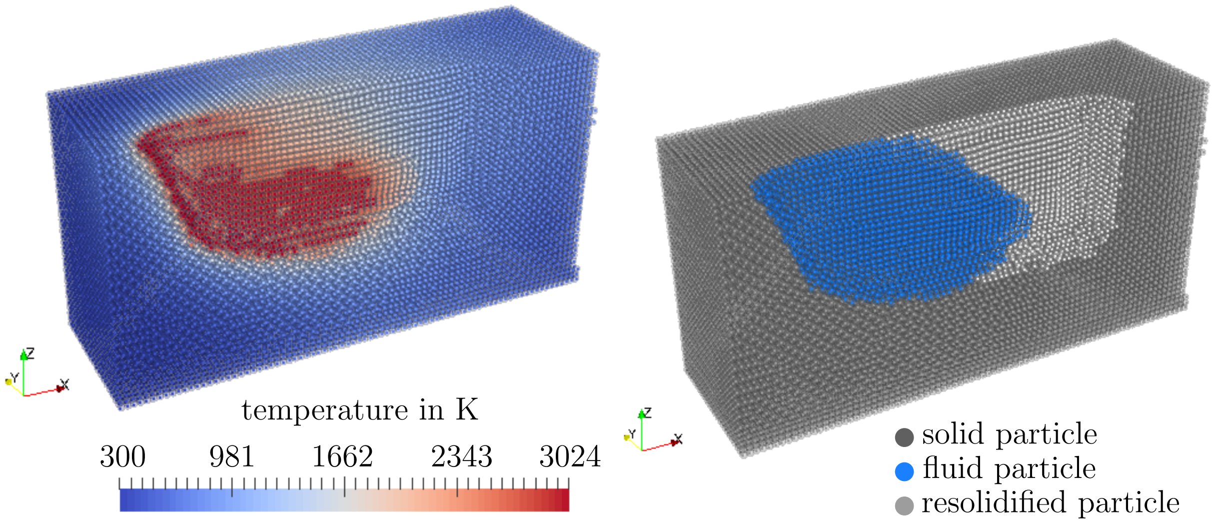


Figure 2: Temperature distribution (left) and different phases (right) during welding of iron at $t = 25\,\mathrm{ms}$ (view of surface and mid cross section).

4.2 Influence of laser beam oscillations on the weld

During the simulations, all process parameters are read at each coupling time step in the general co-simulation approach. Therefore, a complex trajectory of the laser beam is easily specified to keep the simulated welding process as flexible as possible.

Oscillations in y-direction

To demonstrate the model capabilities, in the following example the laser beam is oscillating in y-direction due to a sinusoidal excitation

$$y(t) = A \sin(2\pi f t) \tag{1}$$

in addition to feed in x-direction. The superposed motion of the laser beam is shown in Fig. 3.

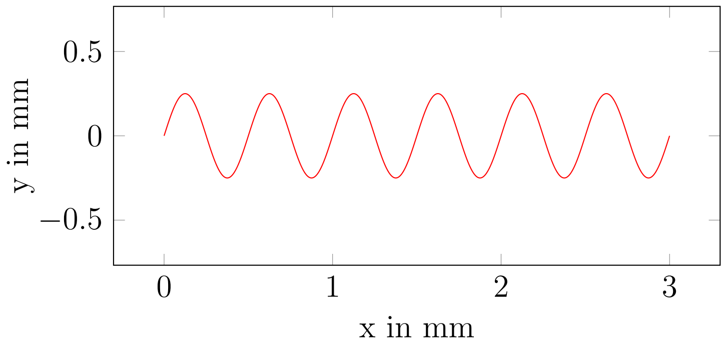
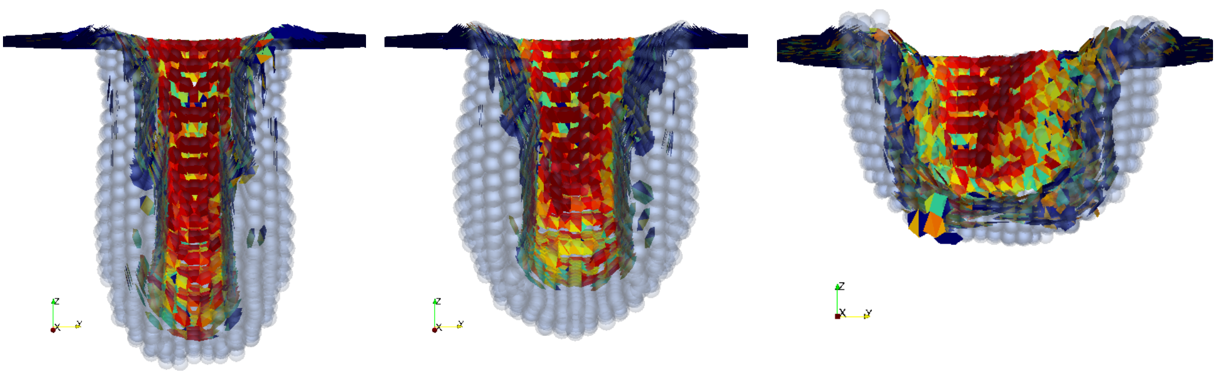


Figure 3: Resulting trajectory of laser beam with a feed rate $v = 6\,\mathrm{m/min}$, an amplitude $A = 250\,\mu\mathrm{m}$, and an oscillation frequency $f = 200\,\mathrm{Hz}$.

With multi-physics simulations, the influence of amplitude A and frequency f of the sinusoidal excitation on the resulting weld may be investigated. The chosen process parameters are $P = 5000\,\mathrm{W}$, $d_f = 200\,\mu\mathrm{m}$, and $v = 6\,\mathrm{m/min}$ as stated in the previous subsection. The simulated process duration is 30 ms, which corresponds to six to fifteen oscillation cycles of the laser beam in the range from 200 to 500 Hz.

In Fig. 4 three different cross sections of the capillaries and weld seams at $t = 20\,\mathrm{ms}$ are depicted, where the amplitude is varied from $0\,\mu\mathrm{m}$ to $500\,\mu\mathrm{m}$, and the oscillation frequency from 0 Hz to 500 Hz. It can be seen that a change in amplitude and frequency while keeping other process parameters constant influences the capillary and weld cross sections to a high extent.



(a) $A = 0$, $f = 0$ (b) $A = 250\,\mu\mathrm{m}$, $f = 500\,\mathrm{Hz}$ (c) $A = 500\,\mu\mathrm{m}$, $f = 200\,\mathrm{Hz}$

Figure 4: Capillary cross section with intensity distribution (red: high intensity, blue: low intensity) and weld cross section in the xy-plane during welding of iron at $t = 20\,\mathrm{ms}$.

The consequences of the variation of amplitude and frequency on the capillary and weld seam dimensions are plotted in Fig. 5. With increasing amplitude the weld seam becomes wider and less deep. The same tendency is observed for an increasing oscillation frequency for this example. However, the influence of the frequency is less pronounced than the influence of the amplitude. These findings agree well with experimental observations obtained for welding aluminum to copper [19]. Furthermore, a higher frequency results in a smoother seam profile along the y-axis without distinct maximum and minimum values. In contrast, the simulation with $A = 500\,\mu$m and $f = 200\,$Hz shows a fissured capillary geometry that gets deeper close to the point of maximum deflections in y-direction.

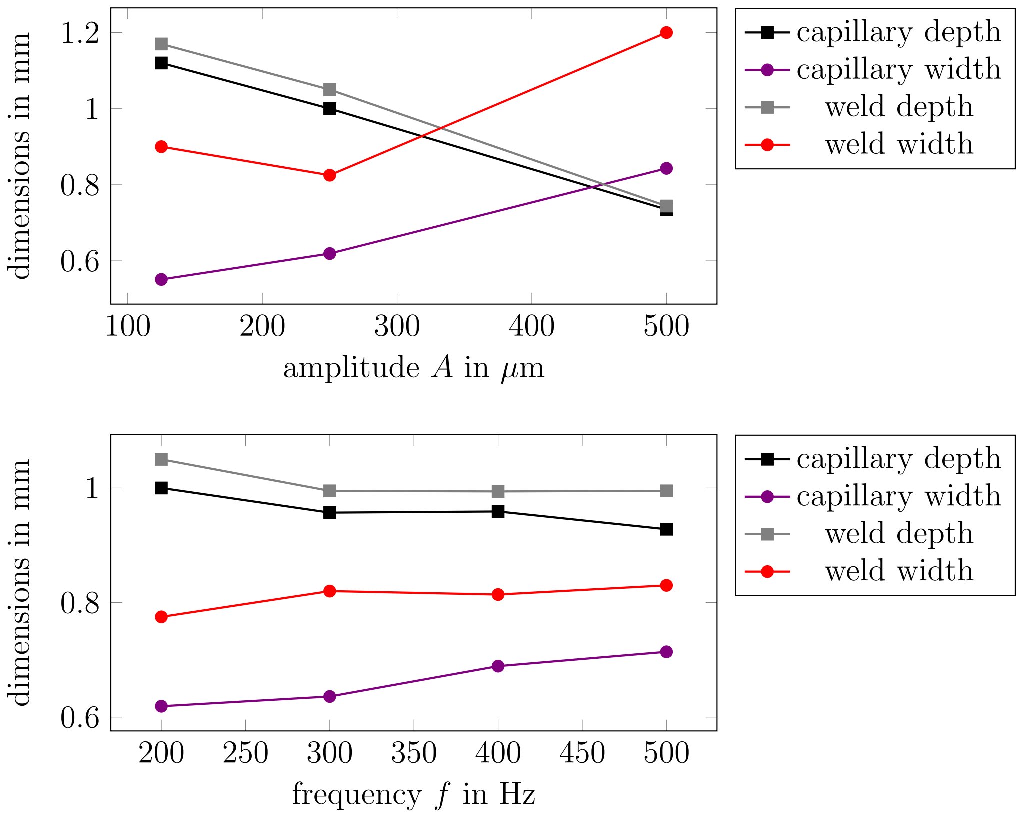


Figure 5: Resulting capillary and weld dimensions depending on the amplitude A in y-direction at a constant frequency of $200\,$Hz (top) and the frequency f at a constant amplitude of $250\,\mu$m (bottom) during welding of iron at a laser power of $5000\,$W.

Oscillations in both x- and y-direction

In a further example the laser beam is oscillating in x- and y-direction due to a sinusoidal excitation with same amplitude A and frequency f, but with a phase shift $\varphi = \pi/2$

such that the beam follows the trajectory

$$\begin{aligned} x(t) &= vt + A\sin(2\pi f t) \ , \\ y(t) &= A\sin(2\pi f t - \varphi) \ , \end{aligned} \tag{2}$$

close to a circular motion as shown in Fig. 6. According to [16], this trajectory is most frequently applied in industrial practice. As an example, such a rotating laser beam is used to suppress spatter and surface voids during welding of copper in [17].

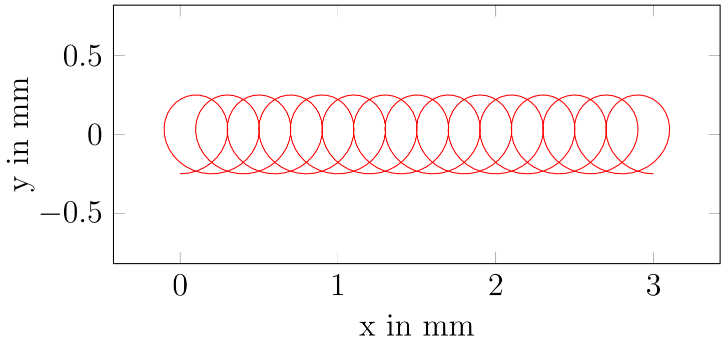
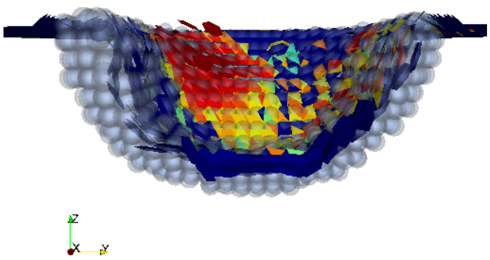
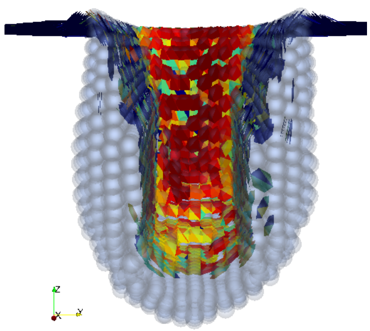


Figure 6: Resulting trajectory of laser beam with a feed rate $v = 6\,\mathrm{m/min}$, an amplitude $A = 250\,\mu\mathrm{m}$, an oscillation frequency $f = 500\,\mathrm{Hz}$, and a phase shift $\varphi = \pi/2$.

The resulting cross sections of the capillary and weld seam at $t = 20\,\mathrm{ms}$ are depicted in Fig. 7a. Compared to the beam oscillation with same amplitude and frequency only in y-direction as shown in Fig. 7b, the weld seam is much wider at the expense of a smaller depth.



(a) $A = 250\,\mu\mathrm{m}$, $f = 500\,\mathrm{Hz}$, oscillations in x- and y-direction



(b) $A = 250\,\mu\mathrm{m}$, $f = 500\,\mathrm{Hz}$, oscillations in y-direction

Figure 7: Capillary cross section with intensity distribution (red: high intensity, blue: low intensity) and weld cross section in the xy-plane during welding of iron at $t = 20\,\mathrm{ms}$.

5 CONCLUSIONS

The process of laser welding is simulated using the SPH method, where both the solid and liquid phase are modeled in detail. The model accounts for significant physical effects such as surface tension, heat conduction, and free-surface melt flow. The phase transitions between melting, solidification, and evaporation are considered together with the absorption or release of the latent heat of fusion and evaporation. The evaporated material is currently not modeled, but the recoil pressure that affects the melt is implemented based on a physical model in [11].

A co-simulation approach is presented by coupling an SPH code with a ray tracer to simulate the laser-material interaction in deep penetration welding. Data is exchanged through a TCP/IP protocol. Additional procedures in the co-simulation are the transformation of intensities into heat source particles interacting with other SPH particles at the surface of the melt, the detection of surface particles, and the subsequent surface reconstruction.

The proposed simulation approach is flexible regarding the specification of process parameters and can be applied for a variety of welding scenarios. This is exemplarily shown for welding with different laser beam trajectories, where the feed is superposed with an oscillating motion in y-direction, and also in both x- and y-direction, resulting in a helical trajectory. The simulations can capture main characteristics of the welding process and predict the weld dimensions and cross section shapes. It is shown that beam oscillations affect the resulting weld seam shape to a high degree. The variation of amplitude has a major influence on capillary depth and width, whereas the influence of frequency on the shape is minor. However, a higher frequency might be preferred to achieve smoother welds.

Even though the simulations deliver valuable estimations on weld dimensions and geometry, the quantitative results still need to be validated. All material parameters are in reality highly dependent on temperature. Therefore, more temperature-dependent material parameters should be used to model the welding process more precisely. One way would be to provide lookup tables and interpolating the values. Another method is to use empirical models that can cover the trends in the changing parameters for a certain type of material or a temperature region. This is an important, but not much investigated topic that needs further research.

In order to make further predictions on the weld quality such as surface roughness, number of pores, and extent of spatter, further extensions in the model are required, especially the inclusion of the gas phase motion and condensation. Both the spatial and temporal resolution for the co-simulation need to be refined to make more qualified statements. In this regard, a reasonable model extension is to use an adaptive SPH discretization scheme that refines the resolution of the workpiece in regions of interest around the capillary, while coarsening the resolution in regions that are far away from the laser beam.

ACKNOWLEDGMENT

The research leading to the presented results has received funding from the German Research Foundation (DFG) in the joint project EB 195/13-1 and GR 3172/18-1 'Modeling of the capillary in laser beam penetration welding with the Smoothed Particle Hydrodynamics Method'. This support is highly appreciated.

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